THE MARS PATHFINDER PROPULSION LINE THERMAL DESIGN: TESTING, ANALYSIS AND PRE-LAUNCH MODIFICATIONS

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ABSTRACT

The Mars Pathfinder (MPF) spacecraft (S/C), launched in December 1996, is the second mission in NASA's Discovery Program. The MPF mission is primarily an engineering demonstration of key technologies and concepts for eventual use in future missions to Mars. The S/C (see Figure 1) is designed to cruise for 7 months on its way to Mars before entering the Mars atmosphere and landing on the surface. The spacecraft has an innovative design which combines the cruise, entry, descent and landing functions into one system. The MPF flight system consists of three essential elements: a Cruise Stage (see Figure 2), that houses the cruise solar panels and Propulsion subsystem, among others; a Deceleration Module that includes a heatshield and a backshell; and, inside the Deceleration Module, a Lander that also contains the Sojourner microrover. The Cruise Stage separates from the Deceleration Module just prior to entry into the Martian atmosphere.

The MPF Propulsion Subsystem is a hydrazine monoprop design with a 2.5 to 1 blowdown. Four, 16.5 inch diameter, spherical diaphragm tanks were loaded with 94 kg of hydrazine and pressurized to 350 psia prior to launch. At this pressure, the eight thrusters each produce 4,45 N thrust (1,0 pound-force) and would produce 1.78 N (0.4 lb-f) thrust at depletion of the propellant supply. Due to a very favorable launch injection, less than 25% of the on-board propellant will be used for trajectory correction maneuvers (TCM's) and attitude control.

As shown in Figure 3, hydrazine flows from the 4 tanks through manifold lines to a system filter and then splits into the two thruster lines. Two latch valves control the flow through the thruster filters and out to the thruster clusters. Each thruster cluster contains 4 thrusters. Mars Pathfinder is a spin stabilized spacecraft and spins about the Z axis (see Figure 3). On one side of the spacecraft, thrusters # 1-4 are aligned at 40 degrees off the -X axis; that is, starting from a - X orientation, the thrusters are pointed 40 degrees toward the + Z direction, 40 degrees toward the - Z direction, 40 degrees toward the - Y direction, and 40 degrees toward the+ Y direction. Thrusters # 5- 8 are aligned in a similar fashion on the opposite, or+ X side of the spacecraft.

Most components of the propulsion subsystem (including the propellant lines) have allowable flight temperature (AFT) limits between 10"C and 45°C. Since the freezing point of hydrazine is 2"C, it is extremely important that all elements of the propulsion subsystem be maintained well above this limit. The upper temperature limit was set to insure predictable thruster performance. Basic S/C thermal design elements in the propulsion system included: multi-layer insulation (MLI) blankets, thermal isolators, heaters and thermostats. The lines were fully blanketed and conductively isolated from the cruise stage with G-10 standoffs. Thermostatically controlled heaters were used to maintain line temperatures above the minimum AFT limit. The MPF cruise stage was designed with an open bus (i.e., propellant lines, tanks, electronics, etc. were all exposed to the space environment). This complicated the propellant line thermal design, since some areas of the

lines had very good views to space and tended to run cold, while others had blocked view to space and tended to run warm.

The entire flight S/C was tested in a simulated cruise environment during the first Solar Thermal Vacuum Test (STV- 1). The mission extreme environments that were tested included a worst-case hot, near-Earth environment (0.99AU, 60° off-Sun) and a worst-case cold, near-Mars environment (1.55AU, 41" off-Sun). Problems with the propulsion line thermal design were revealed during the STV-1 test. In the cold environment, minimum AFT limits were exceeded by as much as 22°C on the thruster lines. In the hot environment, maximum AFT limits were exceeded by 1 "C on the manifold lines.

Thermal design modifications were made to portions of the propulsion lines during a chamber break. On sections of the lines that were identified as problematic, aluminum foil heat spreaders were added and embossed Kapton blankets were replaced by aluminized Mylar/Dacron net blankets. Radiation shields were added over thermostats to isolate them from the warm solar array and increase their views to space. The retest of the S/C (STV-1.1) indicated that thermal performance of the lines in the cold environment was greatly improved. No minimum AFT limits were violated in the cold environment when both the primary and backup line heater circuits were enabled. With only the backup heaters enabled (a simulated fault condition), minimum AFT limits on one of the thruster lines were violated by 5°C. Maximum AFT limits were exceeded by 13°C on the thruster lines in the hot environment.

Lingering concerns about the propulsion line thermal design performance in both the hot and cold environments prompted a need for a detailed analytical thermal model (a 566-node SINDA model) of the lines. The thermal model afforded the following benefits which were not attainable from testing of the flight S/C during STV- 1: a) a high resolution temperature map of the entire prop line system (nodes were placed every 2 inches along the lengths of the lines), b) the ability to determine sensitivity to changes in heat transfer parameters (blanket emittance, standoff conductance, cable conductance, boundary condition temperatures, heat spreaders on the lines, heater dissipation, thermostat set points, thermal mass and radiation shields) and c) the ability to test the design in interim environments that were not the mission extremes, but still might prove to be troublesome (for example, a situation where a line thermostat, with a blocked view to space, was just warm enough to keep its heater is off and caused another section of the line which had a good view to space. to overcool.)

Small-scale tests were done on a section of propulsion line to determine standoff conductance and MLI blanket performance on straight and bend sections of the lines. The original embossed Kapton blankets were found to have blanket effective emittances as high as 0.32 along straight sections and 0.60 near standoffs and cable egresses. Most of this poor blanket performance was due to improper blanket installation and "shorting" of the internal layers due to blanket compression. The properly installed, improved Mylar/Dacron net blankets were found to have blanket effective emittances of 0.10 along straight sections and 0.13 near standoffs and cable egresses.

A preliminary analytical model was built and correlated to the STV- 1.1 data. Model predicts were reasonably close to actual test data and established confidence in our ability to accurately model the flight propulsion subsystem. A final "flight-like" analytical thermal model provided sensitivity data and performance predicts that were invaluable in determining what design modifications needed to be made to the flight system prior to launch.

Having reviewed the model results, the following design modifications were made to the thermal design of the propulsion lines on the flight S/C: 1) the entire line system was reblanketed with the higher performance Mylar/Dacron net blankets, 2) additional blankets were added over standoffs and at interfaces between standoff blankets and line blankets, 3) strips of aluminum foil (0.012 inches thick) were added along the lines to enhance lateral conduction and minimize temperature reductions at standoff locations and cable egresses, 4) radiation shields were added to all lines in areas over thermostats and areas with blocked views to space and 5) a cruise stage rib, that was a standoff attachment point and the location of a cable egress, was blanketed to increase the local line temperatures. With such large scale modifications done to the flight configuration, most projects would have opted to put the S/C back into the chamber for a retest before launch. Given the budget and time constraints on the MPF project, we had to accept a degree of risk and rely on the analysis to prove out the design. Bounding cases were run to establish sufficient margin and confidence in the improved flight configuration,

Flight performance of the propulsion system thermal design has been excellent. No maximum or minimum AFT limits have been exceeded and performance is improved over the as-tested design of STV- 1.1.

The following "lessons-learned" resulted from our experience with the MPF propulsion line thermal design: 1) it was not unreasonable (i.e., too risky) to substitute a detailed thermal analysis of the propulsion lines for a system level retest, since the analysis was carefully done, considered all of the significant heat transfer parameters and properly bounded the problem; 2) embossed Kapton blankets should not be used on propulsion lines where bends and tricky interfaces will result in poor blanket performance; Mylar/Dacron net blankets perform much better in these areas because they can take some compression without "shorting" out the inner blanket layers; 3) locations of thermostats should be carefully considered to make sure that they will adequately control the length of line that they are responsible for; in the very least, they should be placed in the coldest sections of the line to bias the design warmer; 4) aluminum foil heat spreaders are very effective at reducing temperature gradients on the lines; 5) heat shield umbrellas were very effective at reducing the thermal influence of the solar array on the line temperatures and 6) the highest thermal losses along the lines occur at standoffs and cable egresses, where conduction and radiation losses are the highest; special attention should be paid to blanket installation procedures in these locations.